IMPEDANCE SIMULATION AND WAVEGUIDE DAMPING STUDY OF A SUPERCONDUCTING DEFLECTING CAVITY FOR ALS AT LBNL *

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Abstract

Superconducting deflecting cavities are proposed for the generation of sub-pico-second X-ray pulses in storage ring. A 2-cell structure has been simulated to achieve required deflecting voltage and damping waveguide is attached on beam pipe to get low impedance. Detailed simulation notes to calculate longitudinal and transverse impedance in MAFIA and result of different configurations of the damping waveguides are presented.

INTRODUCTION

A scheme to generate short x-ray pulses [1] was proposed some years ago, which requires a correlation to be generated by RF deflecting cavity between longitudinal and transverse phase space within an electron bunch. It is an option for upgrading the existing 3rd generation light sources—synchrotron radiation facilities. For 1.9-GeV electron beam at the ALS of LBNL [2], preliminary studies indicate up to 2-MV deflecting voltage at 1.5 GHz is required. Three to four cells superconducuting RF structures may be required to achieve 2-MV deflecting voltage at 1.5 GHz [3, 4].

A 2-cell azimuthal symmetric structure has been simulated to achieve the design requirements. The cavity geometry is optimized in CST MICROWAVE STUDIO™ for lower peak magnetic field and higher shunt impedance (shown in Figure 1.

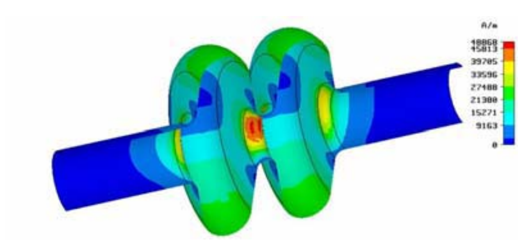

Figure 1: 2cell model with surface magnetic field plotted

The storage ring requires low impedance to avoid beam break up. KEK-B has successfully setup coaxial damper in beam pipe for the lower order monopole mode. Another option is rectangular waveguide as we add on the beam pipe. Both longitudinal and transverse impedance are simulated in MAFIA T3 module, with fourier transform of wakefield integration in time domain. Detailed simulation method and results are presented. The geometry of waveguide is selected to obtain a sufficient damping for the impedance below threshold.

* Supported by National Natural Fundation of China (No.10775080)

IMPEDANCE CALCULATION

MAFIA T3 module is used to calculate the impedance spectrum of both the longitudinal and transverse. After being excited by an gaussian shaped 1-D current, which equals to a rigid gaussian bunch passing through the structure, the transient field inside the cavity will be recorded and wake field (both longitudinal and transverse) on axis will be integrated. The impedance can be calculate from the "wakefield integration" monitor, following the definition of the impedance $Z(\omega)$ by Fourier Transform of $W(z)$ [5]

$$Z_m^{\parallel}(\omega) = \int_{-\infty}^{+\infty} \frac{\mathrm{d}z}{c} e^{-j\omega z/c} W_m'(z), \tag{1}$$

$$Z_m^{\perp}(\omega) = j\int_{-\infty}^{+\infty} \frac{\mathrm{d}z}{c} e^{-j\omega z/c} W_m(z). \tag{2}$$

The dimensionality is $\Omega \mathrm{L}^{-2m}$ for $Z_m^{\parallel}(\omega)$ and $\Omega \mathrm{L}^{-2m+1}$ for $Z_m^{\perp}(\omega)$.

Panofsky-Wenzel (P-W) theorem[6] gives the relationship between longitudinal and transverse impedance:

$$Z_m^{\parallel}(\omega) = \frac{\omega}{c} Z_m^{\perp}(\omega). \tag{3}$$

Comparing with Shunt Impedance

In frequency domain, we calculate the shunt impedance R/Q of the accelerating mode (TM_{010}) which is defined as:

$$\frac{R}{Q} = \frac{V^2}{\omega U} = \frac{(\int_0^D E(z, r=0) e^{-j\omega z/c} \mathrm{d}z)^2}{\omega U}. \tag{4}$$

where V is the voltage a particle sees from the cavity with stored electromagnetic energy U. Actually, for an eigenmode with frequency ω_0, the impedance

$$Z_0^{\parallel}(\omega_0) = \frac{1}{2} \cdot (\frac{R}{Q}) \cdot Q. \tag{5}$$

Eigenmode solvers such as MAFIA E module or Microwave Studio Eigen-solver may be used to calculate electromagnetic field of each eigenmode and then calculate shunt impedance by integrating the E field (Eq.4). If we compare it with the beam impedance from MAFIA T3, we should pay attention to the factor of 2.

For deflecting cavities working at dipole mode, according to P-W theory, we can calculate transverse voltage by longitudinal voltage off axis. And we have a definition of transverse shunt impedance $(\frac{R}{Q})^*_\perp$, where the star mark is used to distinguish from the general definition of beam impedance:

$$\left(\frac{R}{Q}\right)^*_\perp = \frac{V_\perp^2}{\omega U} = \frac{\left|\int_0^L E_z(r=r_0)e^{-j\kappa z}\mathrm{d}z\right|^2}{(\kappa r_0)^2\omega U}. \quad (6)$$

The equation

$$Z_1^\perp(\omega_1) = \frac{\kappa}{2}\cdot(\frac{R}{Q})^\perp \cdot Q, \quad (7)$$

where $\kappa = \omega/c$, should be used in the comparison between MAFIA E and T module.[7]

Some notes of simulation

In MAFIA T3 simulation, we are talking about a Gaussian distribution beam (line charge longitudinal)[8]

$$\rho(s) = \frac{Q}{\sqrt{2\pi}\sigma_s}e^{\frac{(s-s_0)^2}{2\sigma_s^2}}, \left[\frac{\mathrm{C}}{\mathrm{m}}\right], \quad (8)$$

passing an accelerator structure. The equivalent line current (“1dcurrent” source in MAFIA) in time domain and in frequency domain are

$$i(t) = \frac{Qc}{\sqrt{2\pi}\sigma_s}e^{\frac{(t-t_0)^2}{2(\sigma_s/c)^2}}, [\mathrm{A}], \quad (9)$$

$$i(\omega) = Qe^{\frac{\omega^2}{2(c/\sigma_s)^2}}, [\mathrm{C}]. \quad (10)$$

Wakefield generated by the beam can be recorded by wake integration monitor in MAFIA and we get $W^{\mathrm{int}}(s)$ in the unit “[V]”. After normalized by beam moment, we get wake function $W'(s)$ or $W(s)$. For longitudinal impedance, we excite the cavity on axis and record the longitudinal wake. From Eq.(1), we know that

$$Z_0^\parallel(\omega) = \frac{\int_{-\infty}^{+\infty} W_z^{\mathrm{int}}(s, r=0)e^{-j\omega s/c}\mathrm{d}s}{c\cdot i(\omega)}, [\Omega]. \quad (11)$$

For transverse impedance, we excite the cavity off axis at $r = r_0$ and record the longitudinal wake at z-direction on the same position. From Eq.(2) and Eq.3, we have:

$$Z_1^\perp(\omega) = \frac{\int_{-\infty}^{+\infty} W_z^{\mathrm{int}}(s, r=r_0)e^{-j\omega s/c}\mathrm{d}s}{c\cdot\kappa\cdot r_0^2\cdot i(\omega)}, \left[\frac{\Omega}{\mathrm{m}}\right]. \quad (12)$$

Fourier transform of W^{int} can be done using FFT in MAFIA post-processor P Module or in numerical computer codes after the field values are exported.

The wakefield simulation is always computed and recorded in a finite time period τ or length $s_{\max} = c\tau$, the integral does not extend to ∞. We therefore yield a calculated beam impedance z_n for mode n,

$$z_n = Z_n\cdot(1 - e^{-\frac{\tau}{\tau_n}}), \quad (13)$$

where $\tau_n = 2Q_n/\omega_n$ is the natural time constant of mode n. This can be further categorized as the following,[8]

$$z_n = \begin{cases} Z_n & \tau >> \tau_n \\ \frac{\tau}{2}\omega_n(\frac{Z_n}{Q}) & \tau << \tau_n \\ \text{needs two runs} & \tau \sim \tau_n \end{cases}. \quad (14)$$

For a cavity closed with perfect electric conductor, Q is infinite and we can only calculate (R/Q) of each mode.

DAMPING LOMS AND HOMS IN A SC DEFLECTING CAVITY

Overview of Damping Scheme

As mentioned before, the LOMs and the HOMs of the 2cell structure shown in Figure 1 must be damped for beam stability issue. LOMs, which are TM_{010}-like modes, have the highest longitudinal impedance and the frequencies are below the working mode. We add rectangular waveguides whose cut-off frequency is below the frequency of TM_{010} on beam pipe next to both cells. The TM_{010} mode in the cavity has longitudinal electric field on axis and it will strongly couple the electric field of TE_{01} inside the waveguide. The 3D MAFIA model used in time domain simulation is shown in Figure 2.

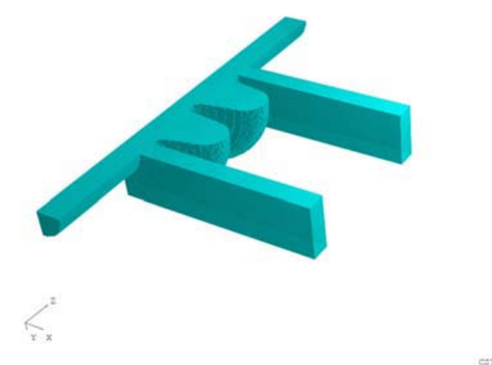

Figure 2: MAFIA model of the waveguide damped 2-cell structure

The dipole modes have two different polarizations, and if the cavity is axial symmetric, those two polarizations share the same frequency. If the working mode is set to give a vertical deflection, the horizontal degenerate mode must be damped and detuned. We may shift the frequency of the unwanted dipole by squash the cavity or using the waveguide set at a specified direction. The unwanted TM_{110} has strong longitudinal electric field at the position horizontally

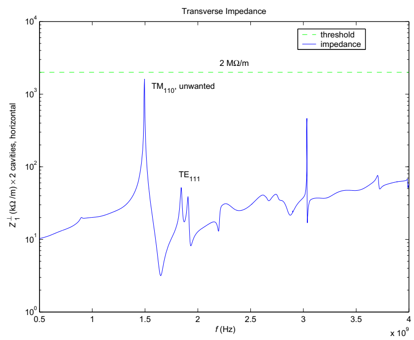

Figure 3: MAFIA T3 result of transverse impedance (horizontal)

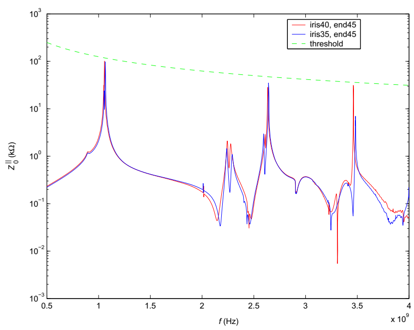

Figure 4: Longitudinal impedance

off axis. So the unwanted mode will couple out through waveguide by TE_{01} just like the LOMs.

The working mode couples TE_{20} in the waveguides. By choosing the waveguide width "a" properly, we can make the LOM propagation mode while the workimg mode is below cutoff. Still long waveguides are needed to get a high Q of the working mode.

TE_{111}, the HOMs with transverse electric field can be damped through this damper much easier than LOMs. Two different polarizations can both be damped. The horizontal one through TE_{10} while the vertical one through TE_{20} in waveguide, and the frequencies are fortunately above cutoff.

MAFIA Simulation Result

MAFIA T3 is used to calculate the impedance. At the first simulation, the transverse impedance of Z_x (horizontal) is below threshold while some harmful modes was found in vertical and logitudinal modes.

Obviously, the radii of end-iris will strongly effect the damping of the LOMs and HOMs. With a big iris, we got lower Q_{ext} but higher magnetic field and will also reduce the (R/Q). We keep the iris between 2 cells (inner-iris) smaller than the end-iris between cell and waveguide, to avoid higher magnetic field. FIG. 4 shows the longitudinal impedance. And we have now damped the modes impedance of modes to an acceptable level by adding the waveguide.

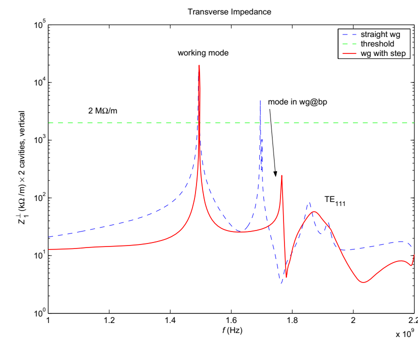

Figure 5: Increased damping using modified waveguide

In the intersection regime of the waveguide and beampipe, there was a dipole mode with high vertical impedance. This mode couples the TE_{20} mode in waveguide, but the frequency is below cutoff and trapped. So we made a step here to push the frequency up to make it propagate through the waveguide. FIG.5 shows the impedance change after introducing the step.

CONCLUSION

Impedance calculation using MAFIA T3 has been accomplished on a waveguide damped 2-cell superconducting deflecting cavity design for X-ray pulse compressing in ALS at LBNL. The wake integration to calculating the impedance spectrum and compare with the stability threshold is a convenient method to simulate LOM and HOM damping. By adding waveguide on a deflecting cavity, the impedance of LOM and HOM mode can reduced to below requirement.

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